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Published in:
Wind energy for the new millennium. Proceedings

Publication date:
2001

Document Version
Publisher's PDF, also known as Version of record

THE NUMERICAL WIND ATLAS — THE KAMM/WAsP METHOD

Helmut P. Frank, Ole Rathmann and Niels G. Mortensen, Lars Landberg, and Erik L. Petersen
Risø National Laboratory
Wind Energy Department
P. O. Box 49, DK-4000 Roskilde, Denmark
phone: +45 46 77 50 13, fax +45 46 77 59 70, e-mail: helmut.frank@risoe.dk

ABSTRACT: This paper will describe the method of combining the Karlsruhe Atmospheric Mesoscale Model, KAMM, with the Wind Atlas Analysis and Application Program, WAsP, to make local predictions of the wind resource. This combines the advantages of meso-scale modeling — overview over a big region and use of global data bases — with the local prediction capacity of the small-scale model WAsP. Results are presented for Denmark, Ireland, and Northern Portugal.
Keywords: Wind Field Simulations, Meteorology, Siting, Models (Mathematical)

1 INTRODUCTION

The Wind Atlas Analysis and Application Program WAsP employs the wind atlas method [11] to make predictions of the wind energy potential from high quality wind measurements. Unfortunately, in many parts of the world there is only poor or no wind data available. On the other hand, global weather models make analyses in these areas, e.g. the re-analysis project at NCEP/NCAR [7]. This analysis is too coarse to be used directly for wind power applications. However, it can provide boundary conditions and external forcing for atmospheric meso-scale models.

Meso-scale models make wind prediction for larger regions of several ten thousand square kilometers. To cover a similar area with measurements would require many stations. This is costly, and it takes a long time to obtain climatological estimates. Therefore, meso-scale models promise to be good tools to obtain an overview of the wind resource of an entire region. However, they can not be used for the siting of wind turbines because the grid resolution of these models is too big.

This paper presents a method of combining both types of models employing the wind atlas concept as used in WAsP. More details can be found in Frank et al. [5]. Previous calculations for Ireland are presented e.g. in Frank and Landberg [4].

2 THE KAMM/WAsP METHOD

The KAMM/WAsP method is the connection of the meso-scale model KAMM and the small scale model WAsP to make local predictions of the wind resource at a site. It combines advantages of the meso-scale model, coverage of a larger region and the possiblity to use globally available data bases, with the high resolution necessary to make local predictions.

The Karlsruhe Atmospheric Mesoscale Model KAMM [1] is used to simulate the wind field for a region. It is forced by data from the global NCEP/NCAR reanalysis [7]. The simulated wind fields are processed into wind atlas files which can be read by WAsP to make local predictions of the wind resource (Figure 1).

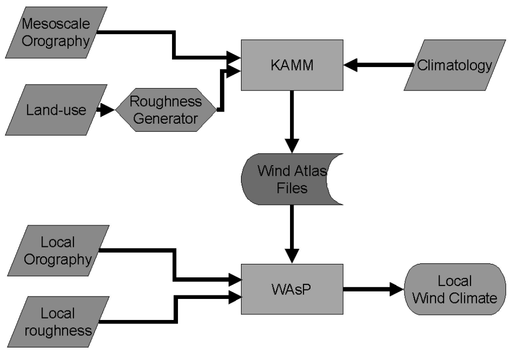

Figure 1: The combination of KAMM and WAsP to calculate the local wind climate.

2.1 Statistical dynamical down-scaling

For the meso-scale simulations we use the statistical dynamical approach of regionalization of large-scale climatology [6] to calculate the regional surface wind climate. It is assumed that the regional surface wind climate is determined by a few parameters of the larger, synoptic scale, and parameters of the surface. This parameter space Numerical simulations of representative situations of the parameter space are performed with the meso-scale model. The meso-scale climatology is calculated from the simulation results together with the frequency of the typical situations.

Important parameters for the surface wind climate in mid-latitudes are the strength and direction of the large-scale pressure gradient, or geostrophic wind, the stratification of the atmosphere, changes in terrain height, and surface roughness. Near coasts, the difference of the surface temperature between land and sea can be important for the development of sea breezes.

The large-scale geostrophic wind is sorted in 12–16 equidistant direction sectors. Each sector is divided in several speed classes of approximately equal frequency per sector. More speed classes are used in more frequent sectors. The stratification of the atmosphere does not change as much as the geostrophic wind. Its importance is measured by the inverse Froude number ${\mathrm{F_r}}^{-1} = NL/U$, where N is the Brunt-Vaisala-frequency, L a typical length scale of the terrain, and U a velocity scale. Hence, stratification is more important at low winds. Therefore, the lowest speed classes in a sector are further divided according to the inverse Froude number. Still, all representative situations with geostrophic wind from one sector have approximately the same frequency.

The frequencies of the classes are determined locally for each point of the large-scale analysis, and interpolated to the grid points of the meso-scale simulations. This accounts roughly for inhomogeneities on the larger scale.

KAMM is forced by the large-scale pressure gradient and temperature distribution and run to an approximately steady state. The simulated surface winds are processed similar to measured wind to produce wind atlas files for WAsP.

2.2 Preparation of wind atlas files

The simulated wind is corrected for roughness changes and orographic perturbations on the KAMM grid as in WAsP Troen and Petersen [11]. The orographic correction is calculated for neutrally stratified, non-rotating flow as in WAsP. The roughness change model is used to calculate perturbations relative to an upstream roughness which is determined as in WAsP.

Extra care must be taken to sample the simulated wind in several wind direction sectors, which is required for wind atlas files. The geostrophic wind classes have a width of some tens of degrees. Hence, on average, a simulated surface wind represents a sector of the same width. If it falls near the boundary of a sector of the wind atlas direction classes, it must be accounted for in both sectors of the wind atlas. Therefore, each simulated wind is split up in a number of wind vectors; typically in 5 values. The split-up winds are obtained by interpolation with the surface wind from the neighboring geostrophic wind class which is "most similar" to the geostrophic wind class which is split. The "most similar" wind class is the one in which the inverse Froude number, determined from the geostrophic wind and the mean stratification, is closest to the inverse Froude number of the split-up geostrophic wind class. The neighboring surface wind is also scaled to the same geostrophic speed with the help of the geostrophic drag law before the interpolation is done. After the simulated winds have been split up, there are enough values (> 500) to calculate frequencies and fit Weibull distributions for different sectors.

3 DATA

3.1 Topography

WAsP employs maps with lines of constant height and/or roughness change lines. The resolution can vary from very high (meters) in areas with complicated topography to low in smooth, homogeneous terrain.

KAMM uses grid maps. Terrain heights for the meso-scale simulations were derived from the GTOPO30 global data base [12], which has a horizontal resolution of 30 arc seconds, i.e. less than one kilometer. The original heights are averaged with a weak Gaussian filter to the resolution of the model grid; 10 km, 5 km, and 2.5 km were used here.

The roughness length of land surfaces is derived from the Global Land Cover Characterization data base [13] using the classification of the US Geological Service. It has a resolution of 1 km^2. A roughness length z_0 is assigned to each land use class. The coordinates are transformed from the Lambert Azimuth Equal Area projection to a cartesian system used in KAMM (UTM, Irish National Grid). Then $\log z_0$ is averaged to the grid size of the simulation to obtain roughness maps for KAMM.

For Northern Portugal the CORINE land-use database was available. It has much higher resolution, and we think it is more accurate. Therefore, it was used for that region.

The roughness length of the water surfaces is calculated from the friction velocity using Charnock's relation [3], and Smith [10] for low wind speeds.

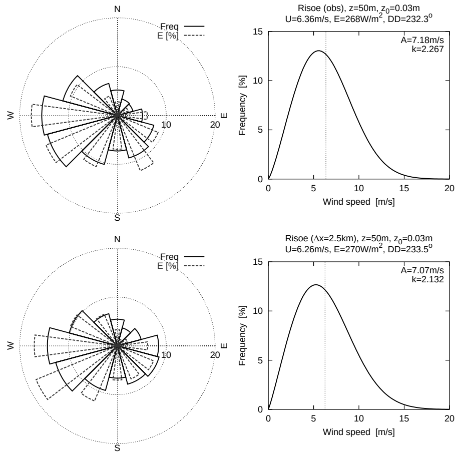

Figure 2: Wind distribution of the wind atlas data for 50 m height above roughness 3 cm from measurements at Risø (top) and from simulations (bottom).

3.2 Atmospheric data

The large-scale forcing for the meso-scale modeling is determined from several years of data from the NCEP/NCAR-reanalysis [7]. In most cases the geopotential height of the 1000, 850, 700, and 500 hPa level and temperature and humidity at 850 and 500 hPa are used. The data is inter- and extrapolated to constant height above sea level and a geostrophic wind is calculated at these heights. Representative classes of geostrophic winds and stratification are determined from the reanalysis data set.

The surface wind observations come from different sources. Rick Watson from University College, Dublin, provided the observed wind data for Ireland. Most of the data analysis for the Danish sites was done within the project "Vindressourcekort for Danmark", contract 51171/97-0002 of the Danish Energy Research Program. Data in Portugal was collected within the JOULE project "Measurements and Modelling in Complex Terrain", contract JOUR-CT90-0067. For one site in Portugal data was provided by Scite-Peristyle, S.A.

4 RESULTS

Here, we shall present results for Denmark, Ireland, and Northern Portugal. They can be roughly categorized as orographically simple terrain (Denmark, though roughness changes are complicated), slightly complex terrain (Ireland, some mountains), and complex terrain (Northern Portugal, very mountainous). Approximately 150 simulations were performed for each region.

Figure 2 shows the wind rose and Weibull distribution of wind atlas data at height 50 m above roughness length 3 cm processed from measured winds at Risø and from simulations for the grid point nearest to Risø. The agreement is good. The frequency of westerlies is overpredicted and that of southeasterlies is under-predicted. In general modeled wind roses are too narrow.

Model wind atlas data as shown in Figure 2 is used by WAsP together with high resolution maps to predict the local wind at a site. Observed energy flux densities, E, [1] are compared with modeled values in Figures 3 and 4 and Table I. Observations are on the abscissa. The predicted values are shown on the ordinate. The vertical and

[1] Actually, the third moment of the wind speed distribution multiplied by a standard air density

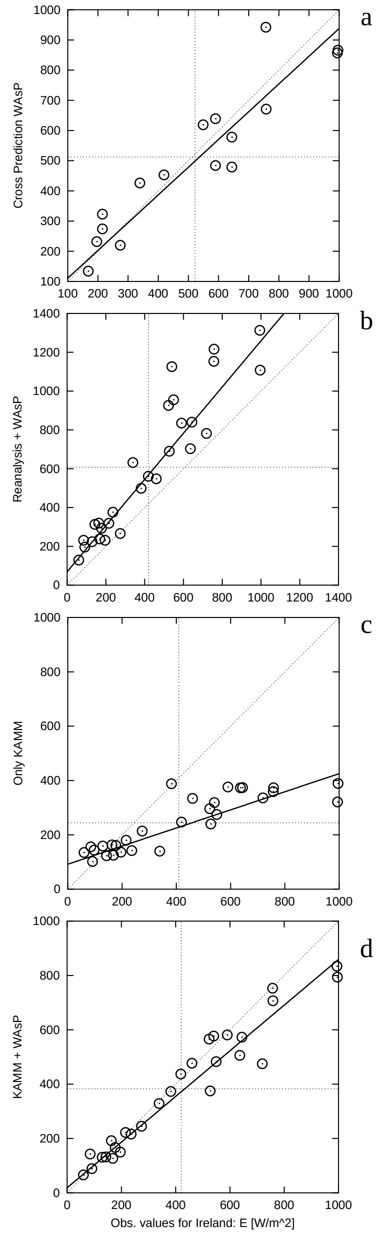

Figure 3: Measured and modeled energy flux densities at sites in Ireland: a) Cross predictions between sites with WAsP, b) predictions with WAsP using wind at 850 hPa from the NCEP/NCAR reanalysis, c) predictions using KAMM, d) predictions of WAsP using wind atlas files from KAMM

horizontal dotted lines are the means of the observations and the predictions. The dotted diagonal would be perfect agreement.

The full line is a regression line which accounts for errors in both data sets. Probably, the biggest observation errors are periods of missing data. For the cross predictions it was assumed that the prediction errors are twice as big as the observations errors. For the other predictions the ratio between observation and prediction error was three.

Four different ways of modeling are compared in Figure 3. The first is the typical wind atlas application with WAsP, where data measured at one site is used to predict the wind at another site. Prediction between sites up to a distance of 25 km apart are shown in the plot.

Table I: RMS values of the relative and absolute prediction errors of energy flux density in % and $\mathrm{W\,m^{-2}}$. Cross predictions (CP) are predictions with WAsP using observations at other sites. NCEP+WAsP employed the wind data at 850 hPa from the NCEP/NCAR reanalysis and WAsP.

Region	Unit	CP WAsP	NCEP +WAsP	KAMM	KAMM +WAsP
Denmark	%	7.5	23.5	47.5	21.9
	$\mathrm{W\,m^{-2}}$	27	101	97	87
Ireland	%	20.4	47.5	53.9	18.3
	$\mathrm{W\,m^{-2}}$	99	236	252	83
Portugal	%	64.0	47.6	82.5	26.9
	$\mathrm{W\,m^{-2}}$	201	218	222	110

In addition to surface observations WAsP can use upper air winds. Here, we used the wind at 850 mbar from the NCEP/NCAR reanalysis. Wind atlas files were made for each 2.5° with the reanalysis data. The wind atlas files were interpolated with the LibIntLT-program [9] to the exact locations of the Irish sites. Then, the surface wind was calculated using these "local" wind atlas files. These predictions overestimate the actual wind resource (Figure 3 b).

One could use the KAMM results directly without any post-processing by WAsP. The simulated mean energy flux densities at the observation heights are interpolated from the nearest grid points to the exact position of the sites. With a simple interpolation no correction for differences of the local roughness and the roughness used in KAMM is made. We compare simulation on a grid with 2.5 km resolution with observations (Figure 3 c). The model cannot see small moutains or hills below the grid resolution, which yield important speed-up effects. Therefore, the performance is bad for the good wind energy sites. Much higher resolution would be necessary to resolve the small-scale speed-up. However, then the simulation could cover only a smaller area with the same amount of computation.

Finally, Figure 3 d shows the predictions using KAMM and WAsP. It yields the best results (see Table I).

WAsP cross predictions and predictions of KAMM plus WAsP for Northern Portugal are shown in Figure 4. The cross predictions look very bad. However, the triangles and crosses show predictions with high differences of the ruggedness index. In such cases WAsP is used outside its operational envelope. Large over- or under-predictions must be expected [2, 8]. If these sites are excluded the errors are only half as big and the regression is good (thick dashed line).

The combination of KAMM and WAsP performs well. The prediction errors are bigger than for Ireland. But, this must be expected in more complex terrain.

The random-mean-square (RMS) value of the difference of observations, E_o, and predictions, E_p, and the RMS of the relative difference, $2(E_o - E_p)/(E_p + E_p)$, are listed in Table I. We can see that cross predictions with WAsP work well in simple to moderately complex terrain. The direct use of reanalysis data in WAsP is good for Denmark, but bad for Ireland and Northern Portugal. Using KAMM without post-processing is bad. The combination of KAMM and WAsP yielded good results in all regions.

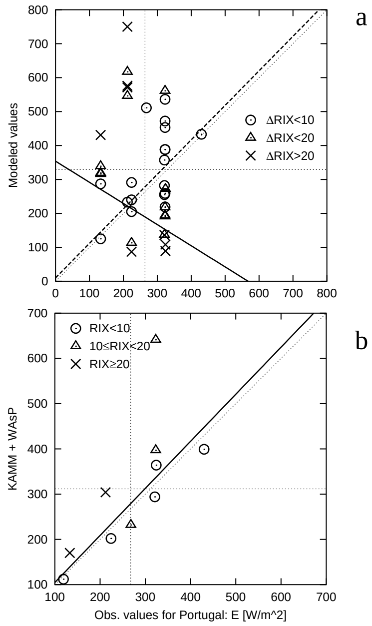

Figure 4: Measured and modeled energy flux densities at sites in Northern Portugal: a) Cross predictions between sites with WAsP, b) predictions of WAsP using wind atlas files from KAMM. The symbols depend on the difference of the ruggedness index, RIX Bowen and Mortensen [2], Mortensen and Petersen [8], between predicting and predicted site, or on the ruggedness index of a site. The thick dashed line is the regression line through the sites with $\Delta RIX < 10$.

5 CONCLUSIONS

It was shown that a combination of KAMM and WAsP yielded good predictions of the wind measured at several sites in Denmark, Ireland, and Northern Portugal. Model data is treated similar to observed data, i.e. the variation of the wind on the grid-scale is removed to a large extent, to produce wind atlas files which are used by WAsP to make predictions of the wind at a specific site. The grid resolution of the meso-scale simulations — here 2.5, 5, 10 km — is only of minor importance for the calculation of the local wind resource.

Cross predictions with WAsP work well in simple to moderately complex terrain. In very complex terrain the error depends on the sign of the difference in ruggedness index [2, 8].

The direct use of NCEP/NCAR reanalysis data in WAsP is good for Denmark. In Ireland and Northern Portugal it over-estimates the wind resource.

Using KAMM without post-processing is not good because the small-scale, local topography is not resolved with a horizontal grid size of 2.5 km. To obtain good results in complex terrain like Northern Portugal, probably, the resolution would have to be higher than 1 km. Then, the meso-scale simulations cannot cover greater regions, which is one of the advantages compared to small-scale models like WAsP.

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This work has been financed through the Danish Energy Research Project "The Numerical Wind Atlas – the KAMM/WAsP Method", ENS-1363/98-0020.

KAMM is used with kind permission of F. Fiedler, University/Research Center Karlsruhe. Some calculations were done on the Fujitsu computer of the Danish Computing Center UNI-C. Computing time was provided through the bonus program of the Danish Research Council.